MuLan: Towards a 1 ppm muon lifetime measurement

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Abstract. The MuLan experiment will measure the lifetime of the positive muon to 1 ppm. Within the Standard Model framework, this will permit a determination of the Fermi Constant to 0.5 ppm. I present an update on our progress and achievements to date.

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The Standard Model of electroweak interactions certainly stands as a triumph of modern physics, due to the impressive agreement among numerous precision particle and nuclear physics experiments performed in the last two decades. During that time, our knowledge of the Fermi constant, G_F, one of the most fundamental input parameters of the model, has not changed. The Fermi constant sets the strength of the weak interaction, and can be cleanly extracted from a measurement of the free muon lifetime [1]

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left(1+\sum_i q_i\right) . \tag{1}$$

Here, the q_i encode the non-weak corrections to a tree level result, including massive phase space (q_0) and QED loop corrections (with q_1 the one loop corrections), while all weak interaction effects are subsumed in G_F. Until recently, extraction of the Fermi constant via this relation was theoretically limited by a 30 ppm uncertainty. A calculation of the two loop QED corrections (q_2 in Equation 1) by van Ritbergen and Stuart [2] has reduced the theoretical uncertainty to the sub-ppm level. Extracting G_F from muon lifetime data is now a statistics limited operation, as no experiments have been performed in the last two decades (see Figure 1).

It is not only technically feasible, therefore, but desirable to improve the experimental situation in both fields with a measurement of the muon lifetime at the ppm level. This is the charter of the Muon Lifetime Analysis, or MuLan, experiment [4], an ongoing effort at the Paul Scherrer Institut (PSI) in Switzerland. The Collaboration intends to record in excess of 10^{12} muon decays, with systematics controlled to better than the statistical uncertainty, with the goal of extracting G_F to 0.5 ppm.

While previous experiments have utilized low rate, DC muon sources, such approach does not scale to our statistics. We require a high rate, time structured muon source that allows us to perform many muon lifetime measurements simultaneously. To this end, we have developed a high rate (7 MHz) beam tune in the πE3 beam line at PSI, and constructed a fast electrostatic kicker [5] to chop the beam. We collect muons on a fixed

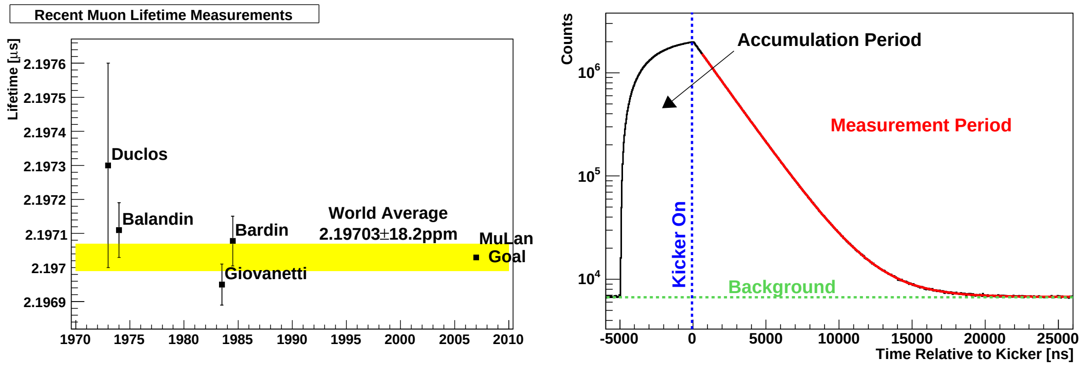

FIGURE 1. Left: A brief history of muon lifetime experiments.[3] The band is the current world average of those experiments. The predicted error bars for the MuLan experiment are not visible at this scale. Right: A muon lifetime histogram extracted from ten minutes of data collected by the MuLan Experiment in 2004.

target for 5 μs (two lifetimes) and then observe decays of those muons during a 22 μs (ten lifetimes) beam off time window in a large acceptance, high granularity detector.

The experiment has been designed from the ground up to minimize or eliminate systematic concerns. In particular, we must

1. Minimize spin polarization and precession effects: Muon beams are inherently polarized, and the momenta of their decay positrons are correlated to their spin direction. If the muon population in our stopping target is allowed to remain polarized, slow spin precession in ambient fields would result in substantial early-to-late effects during the measurement period. We combat these two effects by using a thin target of Arnokrome-3 (AK3), a proprietary alloy with a high internal magnetic field, and a solid depolarizing sulfur target with an externally imposed magnetic field. In both cases, the field is oriented perpendicular to the beam polarization, and rapidly depolarizes the muon population during the beam on period. Regular rotation of the target (and, hence, the field orientation) minimizes the effect of any residual polarization. Additionally, the symmetric detector design allows us to minimize residual polarization effects in the sum of point-wise elements.
2. Reduce pile-up effects: Our detector is a highly segmented, symmetric design, with 170 dual layer detector modules built from fast plastic scintillator organized into a truncated icosahedral (“soccer ball”) superstructure. The high granularity assures a average occupancy of less than 0.1 hits per detector module per kicker cycle. Custom 500 MHz waveform digitizers (WFDs) will allow pulse-to-pulse time resolution of better than 5 ns. Together, these reduce pile-up corrections to better than the 10^{-4} level.
3. Beam off muon arrivals: Muons arriving during the beam off period reduce the signal to background ratio of our data sample. To minimize the number of out-of-time arrivals, we have designed our kicker to operate with a 25 kV potential between the plates, providing a beam extinction in excess of 1000. To eliminate any early-to-late effects on the background at the ppm level from a changing extinction factor, the kicker voltage is regulated at better than the 10^{-4} level for the duration

of the measurement period.

4. Minimize non-target muon stops: Muons which stop outside the high magnetic field of the target are a potential source of residually polarized decays. Even in the absence of polarization, these decay do not have uniform acceptance. To minimize these effects, we have constructed a low mass corridor between the end of the beam pipe and the target, consisting of thin beam windows and a thin Mylar bag between the end of the beam pipe and the target, filled with helium. This construction reduces non-target stops to the 10^{-3} level. In the future, we plan to improve the situation further, bringing the muons to the target completely in vacuum by extending the beam pipe entirely through the detector.

The full MuLan detector was commissioned during a 2003 engineering run. In 2004, the kicker was installed in the πE3 beamline, and we took our first physics data, collecting 10^{10} muon decays. We expect to complete a full analysis of this data before the end of 2006. The statistical significance will be roughly 8 ppm, with comparable systematics. A ten minute subset of our lifetime data from this 2004 run is shown in Figure 1. In 2005 the WFDs were installed and an engineering run validated the full experimental setup, collecting almost 10^{11} muon decays. We are now in the final stages of preparation for a ten week 2006 physics run, during which we expect to record 10^{12} muon decays, with a statistical reach of 1-2 ppm.

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